ULYSSES OBSERVATIONS OF THE RADIAL MAGNETIC FIELD COMPONENT: ABSENCE OF A LATITUDE GRADIENT

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ABSTRACT

The radial component of the solar magnetic field in the southern hemisphere has been measured at Ulysses as it traveled from the equator to -80.2” latitude and returned. The radial component multiplied by the square of the radial distance, i.e., $B_R r^2$, averaged over 77 day intervals (three solar rotations) is approximately constant at -3.5 NT and shows no evidence of a dependence on heliographic latitude. To discriminate against possible time variations, the measurements have been compared with simultaneous measurements being made in the ecliptic by IMP-8 inside negative sectors (sunward-directed fields). The two sets of observations agree very well confirming the absence of a latitude gradient. Since the sun’s dipolar magnetic field component is strong near this phase of the sunspot cycle, it is concluded that magnetic flux from the polar cap is being transported to lower latitudes in the solar wind source region to produce a uniform radial field. Such a configuration would be expected if magnetic stresses are influencing the solar wind flow near the sun and are causing a non-radial deflection. Estimates of the non-radial expansion of the solar wind and of the polar cap magnetic field strength are presented.

A. Introduction

The Ulysses spacecraft left Jupiter bound for the sun's south polar region in February 1992 (Wenzel et al., 1992). The spacecraft slowly traveled southward from aphelion finally reaching the south polar cap (defined as heliographic latitudes above 70") in June 1994 and arriving at maximum latitude (80.2") in September 1994. Ulysses then returned to the equator swiftly as it approached perihelion, journeying from -80" to O" by March 1995, Magnetic field measurements were obtained almost continuously (coverage exceeded 95%) throughout this ascent and descent in latitude. Observations of the radial component, B_R, are presented here. They represent the first comprehensive survey of the latitude gradient and include observations at previously inaccessible latitudes above 30". Preliminary Ulysses results on the latitude gradient have been reported previously (Smith et al., 1995; Balogh et al., 1995).

Previous attempts to investigate the gradient of the magnetic field have been severely restricted in latitude. Furthermore, they have often been frustrated by the large time-dependent variations that are typical of the equatorial region such as those associated with stream-stream interactions. Luhmann et al. (1988) compared B_r values at Pioneer 12 (Pioneer Venus Orbiter) and ISEE-3 when the spacecraft were separated by ≈ 0.3 AU and by latitude differences ranging up to 14° (the difference in the orbital inclinations of Venus and Earth). A periodic dependence on heliographic latitude was found characterized by a north-south asymmetry, the field being stronger in the northern hemisphere. Voyager 1,2 data at large distances in association with simultaneous IMP-8 measurements at lAU were used by Burlaga and Ness (1987) to study the latitude gradient in field magnitude, B, between the equator and 30° north. It was concluded that, at this specific time and location, the field was weaker at higher latitude.

The limited observational opportunities have been supplemented by theoretical models of the solar field and its extension into the heliosphere. One class of models is based on simple solar fields, principally a magnetic dipole, and has explored the effect of stresses exerted by the field and the solar wind on the magnetic field topology (Pneuman and Kopp, 1971). Another class of models is based on extrapolation of observed photospheric fields upward to a source surface at several solar radii where the field is then carried off by the radial solar wind (Hoeksema, 1992). Implicit in the models are various latitude dependence.

Knowledge of the magnetic field gradient has important implications for the physics of the solar wind in the source region. In the hydrodynamic model developed originally by Parker (1953), the field played a completely passive role. However, subsequent models have shown that the magnetic field can have a very significant effect on the solar wind. Another research area that depends on knowledge of the global heliospheric field is the transport and modulation of galactic cosmic rays (Jokipii, 1989).

B. Observations

The relevant measure to use in seeking a latitude dependence is the radial field component, B_R, a characteristic property of the solar magnetic field. It is customary to assume that the solar heliospheric field is radial in or near the source region of the solar wind. The average or steady azimuthal field component, B_T, is a direct consequence of B_R and is also dependent on the solar wind speed. and the angular rotation of the open field lines at the sun or in the corona. Furthermore, B_T is strongly affected by the large amplitude, long period Alfven waves that have been found to be continuously present above -50” latitude (Smith et al., 1995). Since the waves propagate radially, their effect on B_R is significantly *smaller*.

Another advantage to using B_R is the ease of correcting for the radial gradient, a necessary correction because the spacecraft trajectory involves correlated changes in latitude and distance. Conservation of magnetic flux implies that $B_R \sim r^{-2}$. Therefore, the Ulysses measurements have been extrapolated back to 1 AU by calculating $B_R r^2$ along the orbit.

The potential disadvantage in using B_R is the high degree of accuracy required to measure this weak component at large radial distances. $B_{r_0} = 3.5$ nT at lAU implies $B_R =$ 0.14 nT at 5AU. However, the Ulysses Vector Helium Magnetometer has provided exceptional accuracy at the level of a few picoTesla so that B_R is readily measured. The magnetic field investigation is described in Balogh et al. (1992).

To cope with possible time variations, in-ecliptic baseline measurements are needed, Fortunately, magnetic field measurements are available from the earth-orbiting spacecraft, IMP-8 (courtesy of R.P. Lepping). The magnetic field experiment is described in Scearce et al. (1976). The large circular orbit with $r \approx 30 r_E$ lies outside the Earth’s magnetosphere and bowshock and is in the solar wind for ≈ 7 out of ≈ 12 days. The solar wind measurements were identified by inspection of one minute’ averages of the vector field and when necessary by comparing with plasma velocities. Magnetic sectors were also identified so that the field polarity could be determined.

C. Analysis and Results

The strategy was adopted of analyzing magnetic measurements obtained after Ulysses left the low-latitude fan-shaped region in which the variations associated with the heliospheric current sheet, stream-stream interactions and CIRs were dominant. Ulysses passed above the HCS at approximately -30” latitude (Smith et al., 1993) and magnetic field increases associated with CIRs gradually lessened and disappeared at ≈ -50” latitude. From then on, only negative polarities characteristic of the south hemisphere at this phase of the solar cycle were observed. Ulysses measurements of $B_R r^2$ were then averaged over successive time intervals of 77 days (3 solar rotations).

In principle, B_R may also be dependent on longitude even in the free-streaming solar wind at high latitude. Averaging over several solar rotations has the effect of suppressing such a longitude dependence. We examine possible longitude dependence below.

To compare like fields, we restricted the reference measurements at IMP-8 to intervals of inward-directed (negative) fields. We averaged these measurements of B_R over the same time intervals as at Ulysses. To test for the self-similarity of the two data sets, histograms of B_R at Ulysses and IMP-8 were compared. The shapes of the two distributions compared very well (as shown in figure 1), lending confidence to the use of average values at the two locations as being an appropriate measure.

The average values of B_R so obtained are shown in figure 2. Ulysses measurements of $B_R r^2$ are connected by solid lines and the IMP-8 measurements by dashed lines. The data are plotted as a function of time with latitude given along the top scale. This format permits us to incorporate both the ascent to the south polar cap and the subsequent return to the equator in a single plot. Large numbers of measurements are included in the averages. The standard errors are < 0.5 nT initially and decrease to <0.25 nT in 1994. This figure is an extension over the full latitude range of the results reported previously up to -50”.

The obvious features in figure 2 are the absences of both a long-term time variation and a latitude gradient. The shorter period time variations which occur *are* generally well-correlated at the two spacecraft in spite of their large separation in distance and latitude. Both data series can be fit by an overall average of ≈ -3.5nT, a value that is typical of B_r at lAU at this phase of the solar cycle (just prior to sunspot minimum and the end of the cycle).

Absence of a significant latitude gradient, which is contrary to many models of the solar heliospheric field, was examined further by plotting $B_R r^2$ at Ulysses at higher time resolution and as a function of Barrington solar longitude (figure 3). It may be supposed that the effect of the rotating solar dipole would result in a periodic variation in B_R. Considerable fine structure of a random nature is present along with occasional small variations attributable to residual structure. Nevertheless, no significant variation in B_R attributable to the field of a rotating dipole or other longitude dependence is evident. This result supports the absence of a latitude gradient inferred from figure 2.

Absence of a longitude dependence has significant implications for the charged particle measurements being made simultaneously at Ulysses. The energetic particles locally accelerated by CIR shocks and the galactic cosmic rays continue to show periodicities at high latitudes (Simpson et al., 1995). These variations must be accounted for by other than the changing heliomagnetic latitude or latitude relative to a well-defined solar magnetic pole.

Without a significant variation in longitude, we are unable to achieve one of our objectives: to determine the rotation rate (or period) of the polar cap. The various measures of rotation obtained at low to moderate latitudes suggest that the polar caps rotate much more slowly (e.g., Krieger, 1977). Thus far, neither B_R nor "our measurements of the spiral field angle have yielded the rotation rate at high latitudes.

D, Discussion

The absence of a latitude gradient has significant implications for the solar wind and for the various attempts to model the solar-heliospheric field. The presence of a strong dipole component of the photospheric-coronal magnetic field is well-established by the accumulated observations of solar magnetographs especially during the declining phase and minimum in solar activity. Uncertainty in the actual strength of the. polar cap magnetic field has been a persistent difficulty because of the limitations of viewing the relatively weak fields transverse to the line of sight. One of the science objectives of the Ulysses magnetic field investigation has been to obtain a direct accurate measure of the polar field strength. The absence of an observable latitude gradient means that we are unable to accomplish this objective simply by extrapolating the measurements back to the sun's poles.

Given that the polar fields are stronger near the sun, the Ulysses observations imply that such fields are being transported equatorward as part of the solar wind flow to produce a uniform distribution in B_R somewhere between the sun and 1 AU, presumably in the solar wind source region. It follows that the solar wind must also be diverging from higher to lower latitudes as it accelerates outward.

Evidence of such a divergence has been available in the past based principally on x-ray and white light chronograph images which outline plume-like diverging polar magnetic fields and which imply a latitude gradient in the solar wind density (Munro and Jackson, 1977). The Ulysses results show that attempts to extrapolate observed solar wind properties back to the source region need to take account of a strong divergence and cannot rely on extrapolation based simply on radial flow.

Models have been developed in which this divergence is included and is driven by higher pressure over the pole than near the equator. The higher strength of the polar cap magnetic fields will contribute to this effect. Viewed in terms of magnetic pressure, $B^2/8\pi$, there will be a gradient representing a magnetic force directed from the pole toward the equator. An alternative view is that a latitude-dependence of B_R implies a non-vanishing curl and an azimuthal current, j_ϕ. The sense of the field and the latitude gradient ensure that the magnetic stress, $j_\phi B_\theta$, will be equatorward.

In general, a similar gradient in the solar wind pressure will also contribute to the divergence. A model developed by *Suess et al.* (1977), which includes both the plasma and magnetic pressures leads to a uniform magnetic field by the time the solar wind reaches 5 solar radii. However, the internal pressure associated with the divergence overcompensates for the magnetic pressure and the model leads to the opposite divergence, poleward and away from the equator, at greater distances.

The absence of a latitude gradient in B_R at lAU is unlikely to be a coincidence. A uniform field distribution suggests that the magnetic stresses have been relaxed and are no longer effective. Since this end point would be expected if the magnetic stresses were acting alone, it follows that magnetic stresses must be dominating the solar wind divergence somewhere above the corona, probably in the solar wind source region itself. The realization that the accelerating solar wind must be treated as a magnetized plasma in which the field plays a significant role is now seen as a complicating but necessary factor in solar wind models.

The Ulysses results raise serious questions about another class of models, the various source surface models. They typically involve extrapolation of measured photospheric magnetic fields to a surface (or surfaces) at which a boundary condition is applied such as the elimination of non-radial fields. The extrapolation is based on a spherical harmonic , representation of the field and currents are assumed to be absent between the photosphere and the source surface, a dubious assumption in view of the Ulysses observations.

These models were devised to reproduce the observed sector structure in or near the ecliptic and parameters in the models were adjusted to render this agreement (Hoeksema et al., 1983). They have been successful in predicting the shape of the neutral line on the source surface or, equivalently, the inclination of the heliospheric current sheet with which the neutral sheet is identified. However, they have failed to yield reasonable values for the strength of the heliospheric magnetic field above and below the neutral sheet.

Attempts have been made recently to improve the. agreement with the observations by adding the field of the HCS in an ad hoc manner (Wang, 1993; Zhao and Hoeksema, 1995). The current sheet produces a B_R that is uniform, i.e., independent of latitude, so that the field measured by Ulysses can be attributed to the HCS alone. (To avoid confusing cause and effect, it is correct to say that a uniform B_R which reverses sign at the equator gives rise to the sheet current.) However, the effect of the dipole-like photospheric fields leads to a latitude gradient with stronger fields at higher latitudes. Clearly, the limitations of these models need to be reexamined.

The Ulysses observations yield an accurate measure of the flux of open magnetic fields in the south hemisphere. The constant B_R makes this determination simple, i.e.,
$\phi = 2\pi B_r r^2 = 2\pi (3.5 \times 10^{-9})(1.5 \times 10^{11})^2 \approx 5 \times 10^{14}$ webers.

This result is potentially useful in providing an estimate of the solar wind expansion (or spreading) factor, an important parameter which quantifies the flow divergence, In principle, this factor can be obtained from knowledge of the surface area and magnetic field strength, i.e., the magnetic flux, of the south polar coronal hole, The expansion factor is the ratio of the two spherical areas or solid angles occupied by this flux near the sun and as measured by Ulysses.

In lieu of such information for the south polar coronal hole, simple models of the polar magnetic field can be used to obtain an estimate of the solar wind divergence and the polar cap field strength. The following illustrative calculation will assume azimuthal symmetry so that the solid angles associated with the polar coronal hole, Ω_p, and the fast solar wind, Ω_F, are given by the co-latitude of their equator-most edge. We assume that the fast wind occupies the region above 45° latitude in reasonable agreement with the appearance of a continuous speed of ≈750km/sec. The corresponding solid angle above 45° is then $\Omega_F = 2\pi(1-\cos(\pi/4)) \approx 0.6\pi$ ster. The magnetic flux contained within this solid angle is $\Phi_F = r_0^2\ Br_o \Omega_F \approx 0.6\pi r_0^2\ Br_o$.

To estimate the flux from the polar cap, we represent the radial field by $B_R = B_p \cos^n(0)$ where B_p is the field strength at the pole at distance r_s, which is taken to be a solar radius. The index n will be allowed to range from n=0, a uniform field within the coronal hole, to n=8, a value proposed by Svalgaard et al. (1978) based on photospheric field observations and which presumably represents extreme concentration of magnetic flux near the pole. The case n=l corresponds to a dipole field,

The magnetic flux passing outward through the polar cap is given by

$$\Phi_p = 2\pi B_p r_s^2 \int_0^{\theta p} \cos^n(\theta)\sin\theta\ d\theta.$$

$$= 2\pi B_p r_s^2 (1-\cos^{n+1}(\theta_p))/(n+1).$$

This flux occupies a solid angle, $\Omega_p = 2\pi(1-\cos\theta_p)$. Equating the two fluxes, $\Phi_F = \Phi_p$, implies that

$$\cos^{n+1}(\theta_p) = 1-(n+1)(r_o/r_s)^2(Br/B_p)(\Omega_p/2\pi).$$

For assumed values of B_p and n, θ_p can be calculated from this expression and used to obtain Ω_p. The expansion factor, $S = \Omega_F/\Omega_p$, is plotted in figure 4 for various combinations of B_p and n.

For a uniform field (n=O) with B_P=2 Gauss inside the polar coronal hole, S=2. However, S is significantly larger for stronger fields. Thus, B_p=5G implies S=3 while 10G implies S=6. Furthermore, S is essentially independent of n. We conclude that for reasonable field strengths exceeding a few Gauss at the pole, a large expansion of 3 or more is implied.

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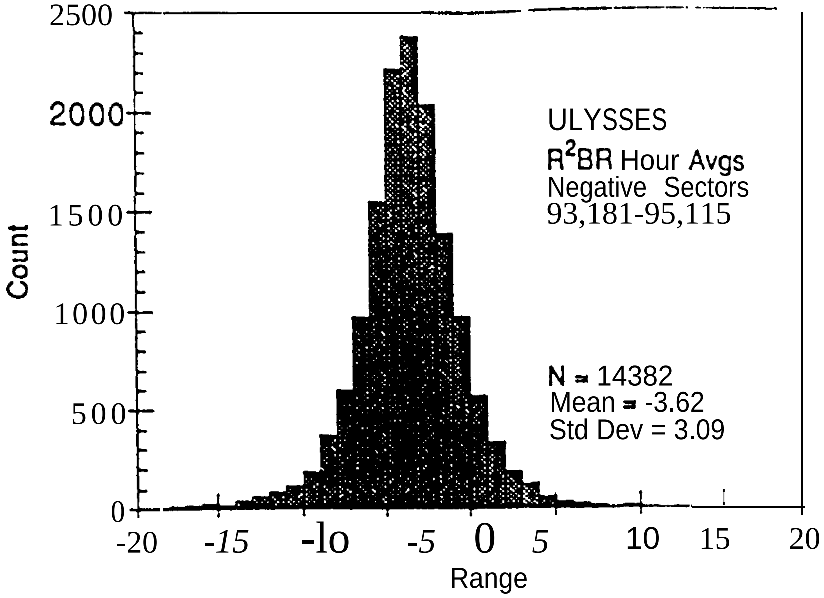
Figure Captions

Fig. 1 Probability distributions at Ulysses and IMP-8. Histograms of B_R averaged over one hour are shown over the interval from 1993.5 to 1995.3. The radial components at IMP-8 correspond to times when the spacecraft was inside negative magnetic sectors. Since B_R is positive when directed outward from the sun in Solar Heliospheric coordinates, the probable values and averages are negative at both spacecraft. The probability distributions are very similar in spite of the large separation in heliolatitude. The means at Ulysses and IMP are -3.6 and -3.4, respectively.

Fig. 2 Radial Field components at Ulysses and IMP-8. The circles and solid lines represent 77 day averages of $B_R r^2$ at Ulysses over the interval from 1992 through 1995. The heliographic latitude of the spacecraft shown along the upper scale indicates the descent from -10” to -80.2” and the rapid return to the equatorial region. The IMP-8 measurements (squares and dashed lines) are for the same time intervals but are restricted to measurements made in negative sectors. The close correspondence between the two sets of measurements is striking. There is no evidence of a significant latitude gradient at any time or latitude separation. The absence of a secular time variation over the 3 year period is attributable to the observations being made near sunspot minimum.

Fig. 3 B_R at Ulysses as a function of Barrington Longitude. Hourly averages of B_R are displayed for 6 solar rotations centered on maximum heliographic latitude. The time and latitude at the start of the rotation arc shown at the left of each panel. The Barrington longitudes correspond to the subsolar location of the spacecraft as it is unnecessary to take the constant solar wind speed of ≈ 750 km/s into account. In spite of 5-point smoothing, random short period variations are present, caused by the Alfven waves above ≈ 45”. No long period sinusoidal variation indicative of a dependence of B_R on longitude is evident during any of the solar rotations.

Fig. 4 Solar wind expansion factor deduced from the magnetic flux observed in the polar cap. The expansion (spreading) factor, S, is the ratio of two solid angles. One (Ω_F) is that occupied by the fast solar wind corresponding to colatitudes above 45”. The other (Ω_p) is the solid angle of the sun’s polar cap that would produce the same magnetic flux as observed by Ulysses inside Ω_F. The magnetic flux issuing from the polar cap is calculated from the model described in the text. It depends on two parameters, the field strength at the pole (B_p in Gauss) and the index (n) which describes the distributions of flux within the polar cap, i.e., B_p is proportional to $\cos^n\theta_p$, where θ_p is the colatitude (shown on the right hand scale). A uniform field corresponds to n=O and a dipole field to n=l. Thus, for a dipole field of 5 Gauss, $S = \Omega_F/\Omega_p \approx 3$ corresponding to colatitudes of 45” and 25”.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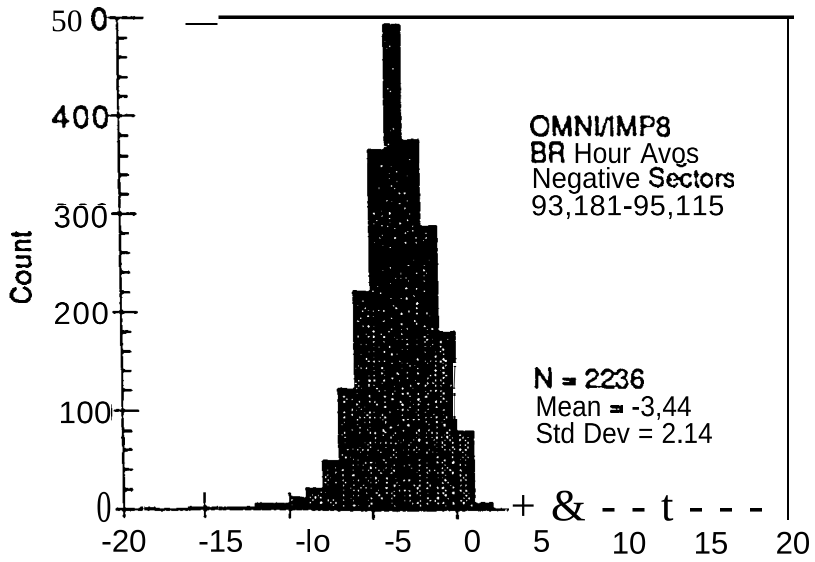
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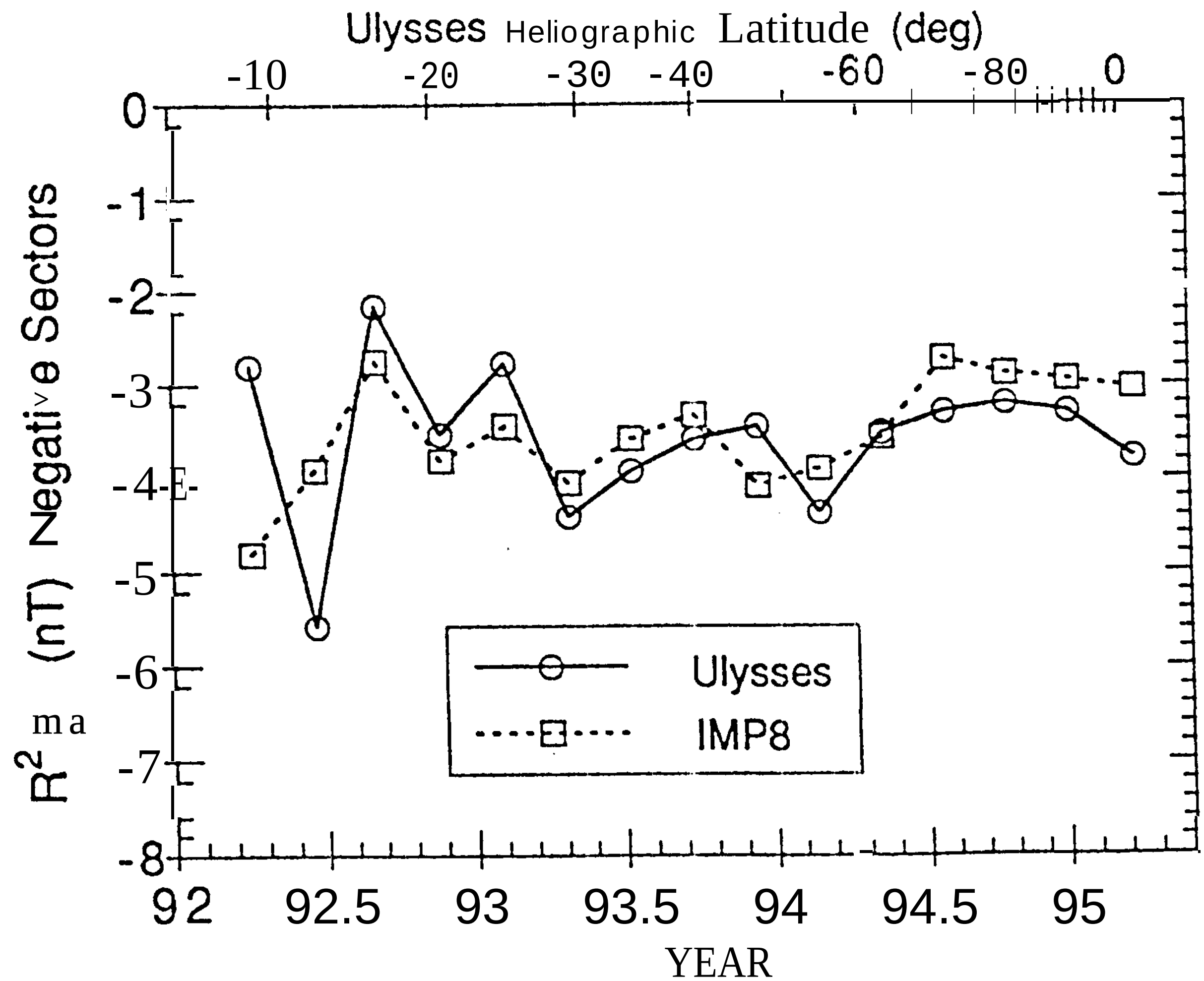
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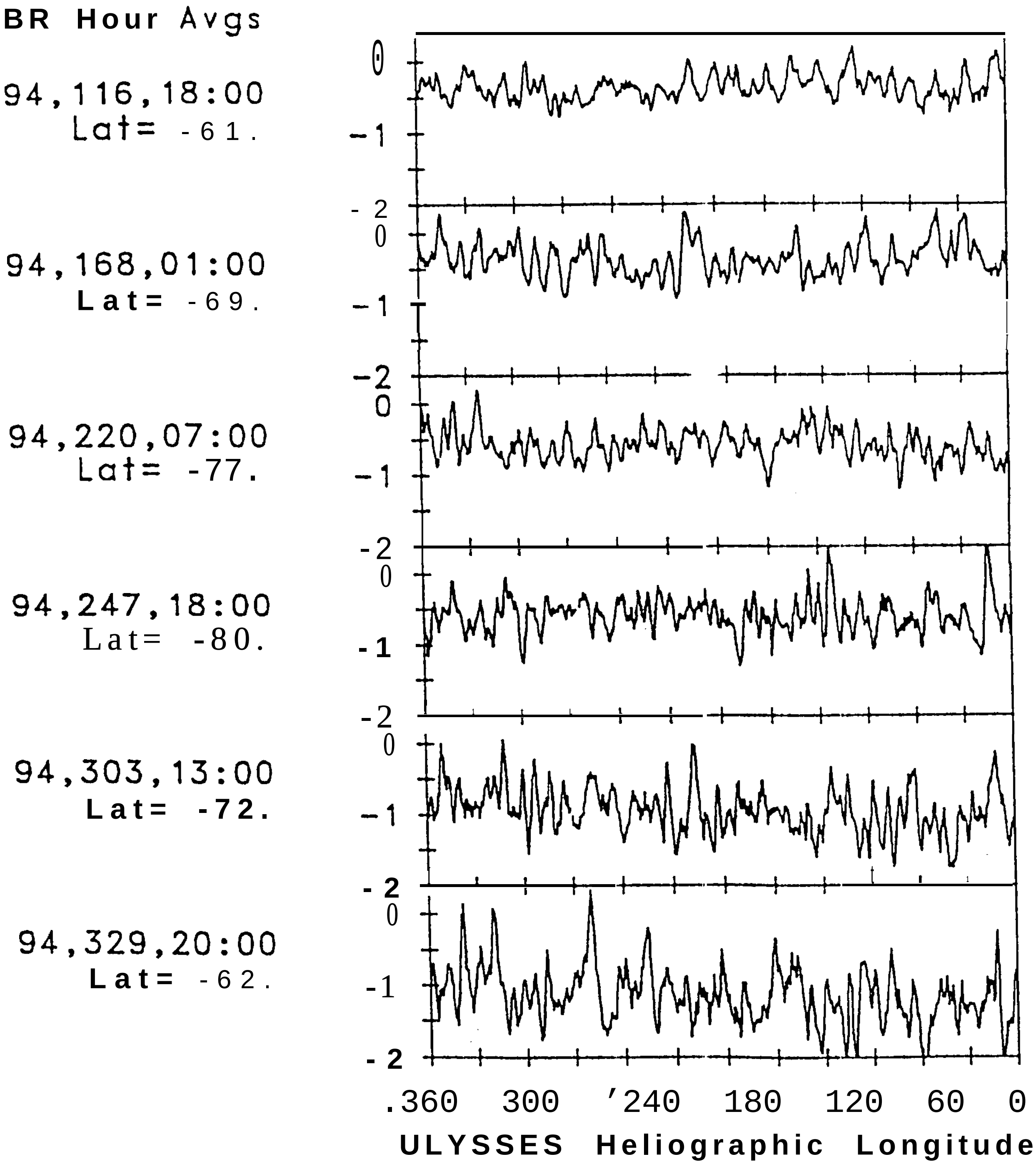
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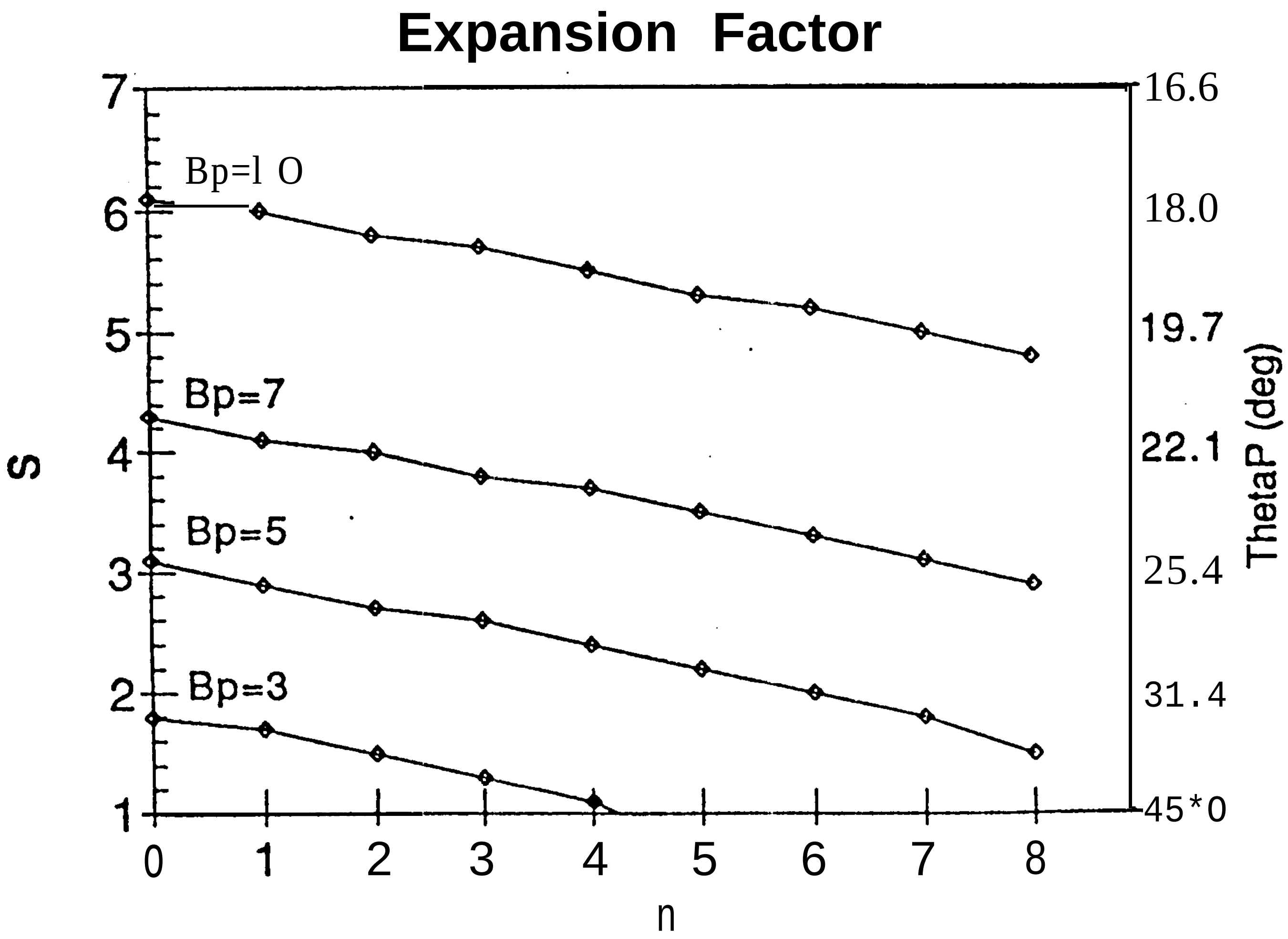

Expansion Factor
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ThetaP (deg)
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Bp=5
Bp=3
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22.1
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31.4
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